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Roll Attitude Control of a Space Vehicle

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ABSTRACT - *Guided missiles are space-vehicles carrying war-heads. Three attitudes- the roll, pitch and yaw have to be continuously controlled in a space flight. This is done by using automatic control systems. The design procedure for roll attitude control of a guided missile is the subject of the paper. This is extremely important for following proper trajectory and hitting the target. Two designs have been advanced. In the first design, there is no constraint on velocity error. The design has been optimized by simultaneous variation of forward path gain and the rate feedback. In the second design, the velocity error has been specified. It has been optimized by simultaneous variation of the rate feedback and the parameters of a lead compensator.*

Keywords - *Rocket, Guided missile, Roll attitude control, Overshoot, Phase margin, Gain margin*

I. INTRODUCTION

Space exploration was once upon a time the dream of the scientists and engineers. Even exploring the aerial space was far from their reach. But, now it has become a reality due to recent achievements in the field of aviation and space travel.

Space travel may be the sub-orbital, orbital or in the outer space. It has been made possible due to the invention of powerful controllable rockets. The two pioneering countries in planetary exploration are Soviet Russia and USA. After successful landing on the lunar surface by humane and unmanned voyage to mars, now people are thinking about space shuttles with reusable space vehicles. They are expected to be commercialized within a short period of time [16].

A guided missile is a military rocket carrying weapons or instruments. They are directed towards a target. The direction of flight can be changed while they are in motion. The rocket is similar to a guided missile but it is an unguided warhead [1][2][3].

A rocket or a rocket engine is essential for space travel. It is a self-propelled device that carries its own fuel, as well as oxygen, or other chemical agent, needed to burn its fuel. A rocket engine is the most powerful engine for its weight. Other forms of propulsion, such as jet-powered and propeller-driven engines, cannot match its power. Rockets can operate in space, because they carry their own oxygen for burning their fuel. Rockets are presently the only vehicles that can launch into and move around in space [4][5].

II. THE GUIDED MISSILE –TYPE AND COMPONENTS

The guided missiles vary widely in size and type, ranging from large strategic ballistic missiles with nuclear warheads to small, portable rockets carried by soldiers. Most of them carry military warheads, but some of them may carry scientific instruments only for the purpose of research.

The components of a guided missile are: power source, guidance and control mechanism, and warhead or payload. The power sources are self- contained rockets or air-breathing jet engines. The guidance and control depend on the type of missile and the nature of the target. The guidance is rather simple for a fixed target, but it is complex for a moving object. For a moving target the space coordinates of the moving object have to be sensed continuously and accordingly adjust the guiding and control mechanism. A variety of sensors have to be used in such cases. Payloads are generally warheads designed for specific missions [16].

III. GUIDANCE AND CONTROL OF MISSILES

Missiles are guided toward targets either by remote control or by internal guidance systems. Remote control missiles are linked to target locator through trailing wires, wireless radio, or some other type of signal system. Internal guidance systems have optical, radar, infrared, or some other type of sensor that can detect signals from the target. Missiles have some type of movable fins or airfoil that can be used to direct the course of the missile toward the target while in flight. The inertial guidance systems of ballistic missiles are more complex. Missile velocity, pitch, yaw, and roll are sensed by internal gyroscopes and accelerometers, and course corrections are made mechanically by slightly altering the thrust of the rocket exhaust by means of movable vanes or deflectors. In larger rockets, small external jets are also used to alter direction [9][10][11].

IV. DESCRIPTION OF THE SYSTEM

The roll attitude control of a space vehicle has attitude and rate gyros. The system is shown in fig. 1.The transfer function of the booster rocket, the amplifier gain and the actuator gain are given. We are looking for the best possible values of the gain, the rate feedback and the parameters of the compensators against two different specifications. The analysis has been made by using MATLAB tools.
The specifications for the designs are given below:

a. Specifications:

For the first design there is no constraint on velocity error. As the system is of type 1, the position error is zero and the value of gain does not affect the steady state error. Our aim is to get a phase margin of 60^o or more, a gain margin of 30 db or more and a percent overshoot below 0.25 %.

For the second design, the velocity error is to be kept within 2%. The gain has to be fixed up accordingly. We are aiming at a gain margin of at least 20 db and an overshoot below 1%.

b. Mathematical description

The loop transfer function of the system [6][7][8] is given as:

$$GH(s) = \frac{10K(K_p + K_d s)}{s(s^2 + 8s + 4)} \quad (1)$$

And the closed loop transfer function of the system is given as

$$M(s) = \frac{10K}{s^3 + 6s^2 + (10KK_d + 8)s + 10KK_p} \quad (2)$$

We find out the value of the gain and the feedback factors for best possible performance using a specially constructed MATLAB program. Initially we consider that there is no constraint on velocity error. By an iterative process, we fix up the values of feedback factors at: *Kp*=1; *Kd*=0.5 and the gain at *K*=1.6

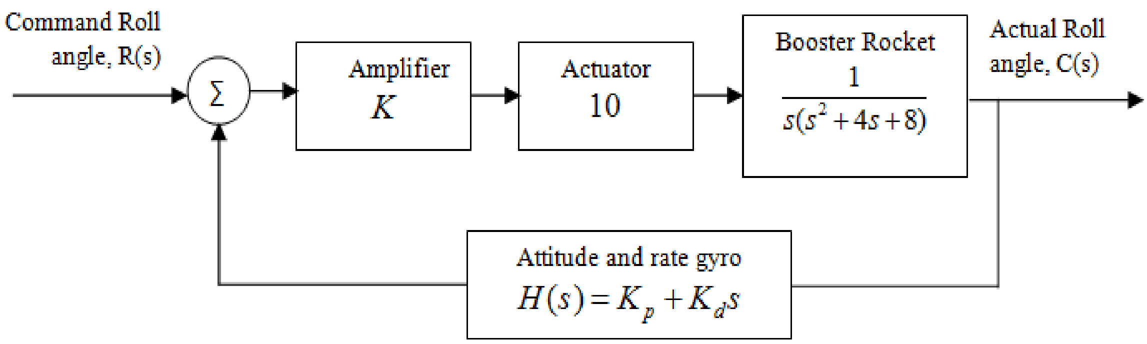

Fig 1 Roll attitude control of a missile: block diagram

V. FINDINGS FROM THE MATLAB-PROGRAM

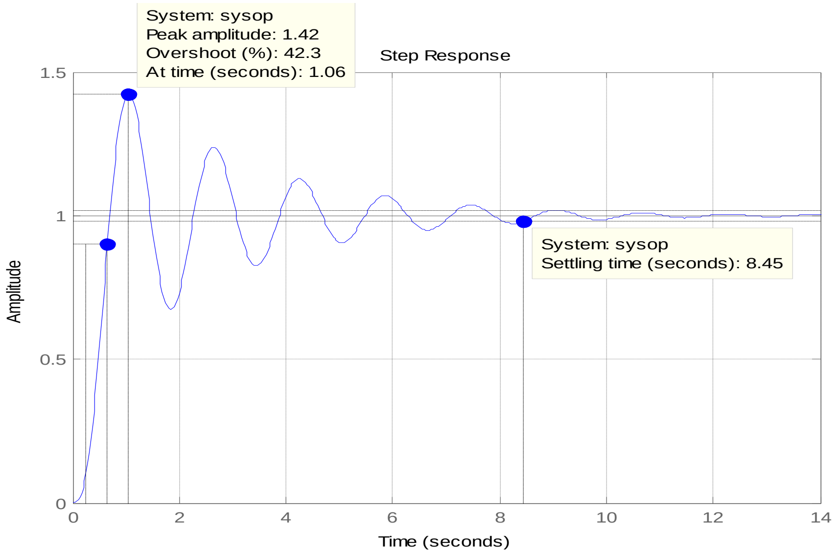

Fig. 2. Time domain response at K = 5.0, K_d = 0.2

The MATLAB programme [12][13][14] has been used to find out the amplifier gain and feedback coefficients of the missile for optimal or best possible performance [15].

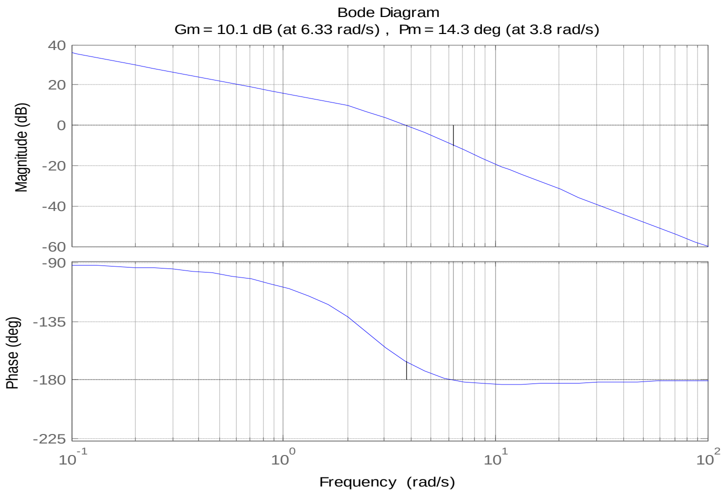

Fig. 3. (Bode plot) at K = 5.0, K_d = 0.2

At first we choose, the value of forward path gain: K = 5.0 and the coefficient of rate feedback, K_d = 0.2; the time and frequency domain performances are given in fig. 2 & 3. The root locus is given in fig. 4

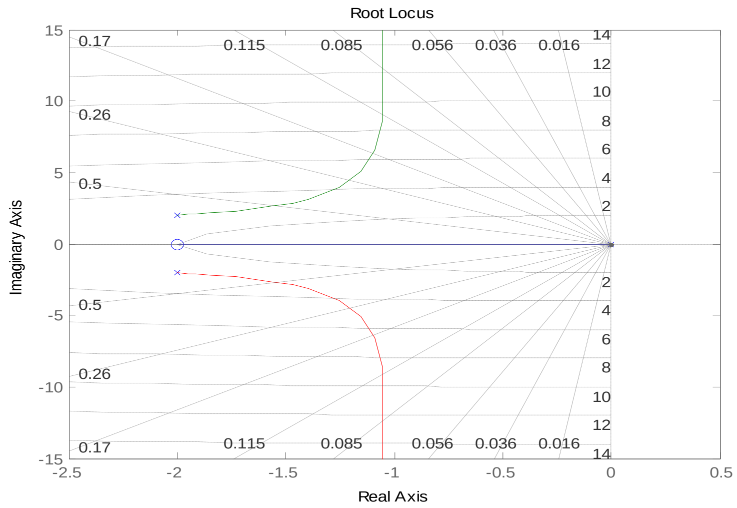

Fig. 4 Root Locus

The system is stable but the time domain performance is not acceptable. The %overshoot is 42.3% and the settling time is 8.45 sec. The stability margins are also much lower than specified. The gain margin is only 10.1 db and the phase margin is only 14.3^o for the chosen value of the gain and rate feedback. So we reduce the gain to K =3.0 and rate feedback, K_d =0.3 With these values the time-domain and frequency-domain responses are given in fig. 5 &6.

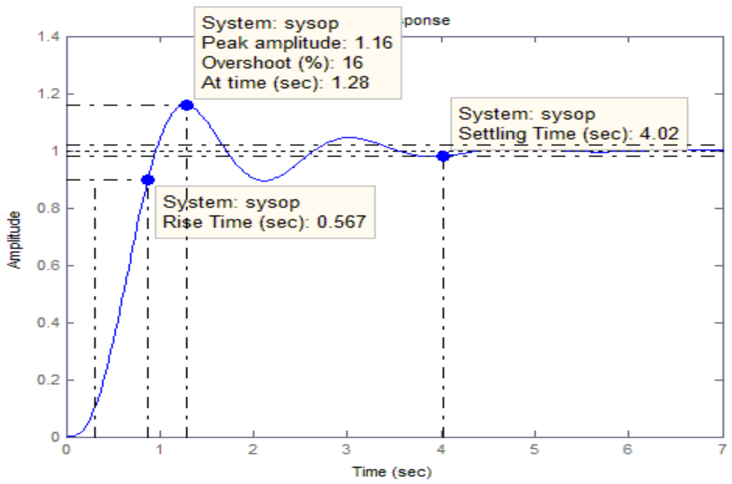

Fig. 5. Time domain response at K = 3.0, K_d = 0.3

At this value of gain, K = 3.0, and rate feedback, K_d = 0.3, the percent overshoot has reduced to 0.159 (15.9%) and the peak time is 1.29 sec. The settling time is only 4.02 sec. The phase margin is 33.9^o and the gain margin is infinity. This design is better than the preceding one.

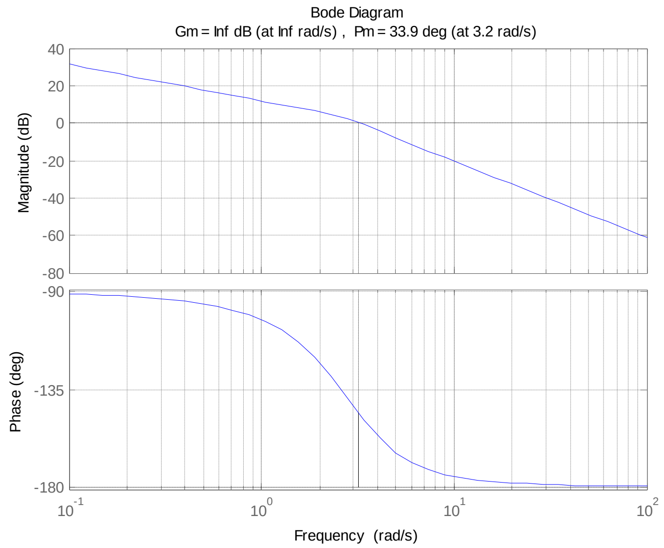

Fig. 6 Bode plot for K = 3.0, K_d = 0.3

But the design specifications have not been fulfilled. So we further reduce the gain to: K = 2.0 and increase the rate feedback to: K_d = 0.4; With these values, the time and frequency domain responses are given in fig. 7 and 8.

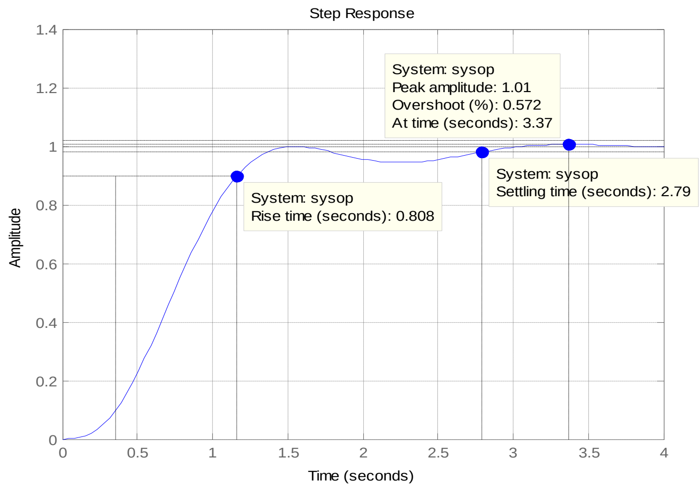

Fig. 7. Time domain response at K = 4.0, K_d = 0.4

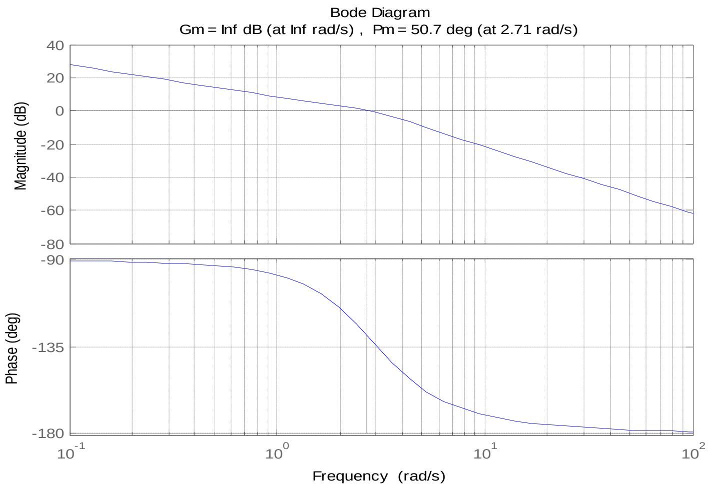

Fig. 8: Bode plot for K = 4.0, K_d = 0.4

Now the damping is almost critical- the system has only an overshoot of 0.572% against a peak time of 3.37 sec; the settling time is only 2.39 sec. The phase margin increased to 50.7°. The t-domain behavior is satisfactory but the phase margin is less than specified. So we further reduce the forward path gain to: K = 1.6 and rate feedback, K_d = 0.5

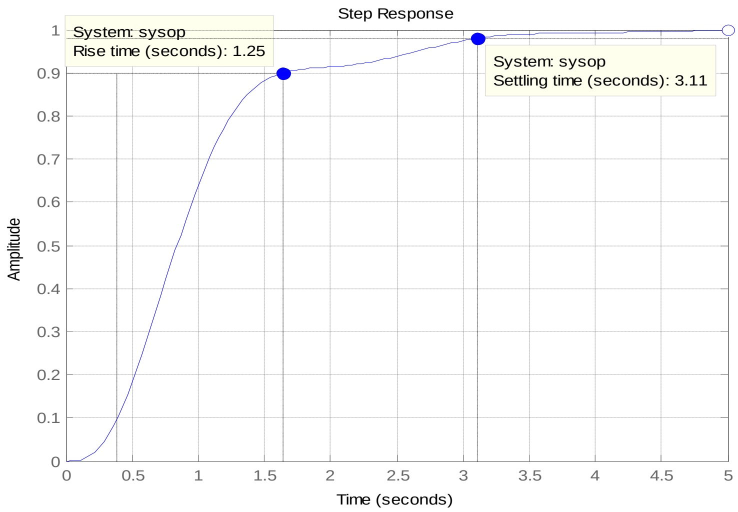

Fig. 9: t-domain response for K = 1.6, K_d = 0.5

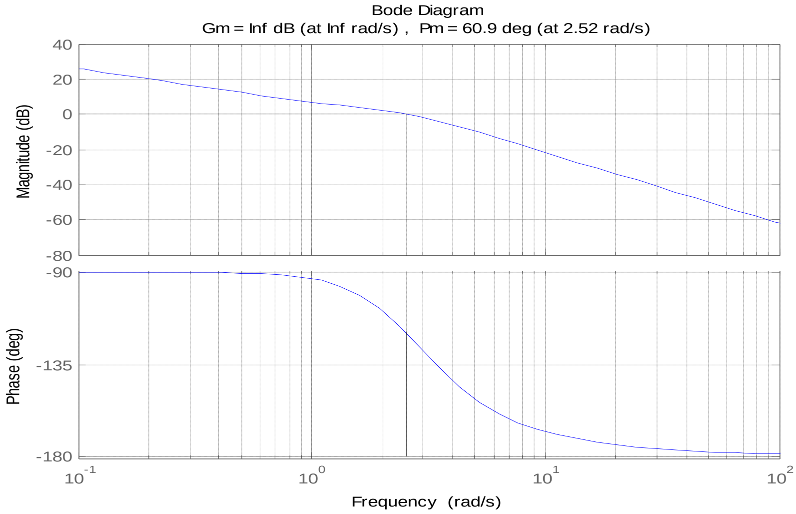

Fig. 10: f-domain response for K = 1.6, K_d = 0.5

Now, the system is slightly over damped. The overshoot has become nil without much loss in other t-domain parameters. The settling time has increased to 3.11sec. and the rise time to 1.25 sec. But the specification for phase margin has been satisfied. Now it is 60.9^0 which is more than 60^0. the findings have been given in table 1.

TABLE 1 COMPARATIVE VIEW (ROLL ATTITUDE CONTROL)

Syst. Gain, K	Rate fb K_d	Peak Time t_p	Peak Over shoot	Settling Time t_s	Gain/ Phase margin
5.0	**0.2**	1.06 s	42.3 %	8.45 s	10.1 db /14.3^o
3.0	**0.3**	1.29 s	15.9 %	4.02 s	Inf/ 33.9^o
2.0	**0.4**	3.37 s	0.57%	2.79 s	Inf/ 50.7^o
1.6	**0.5**	n.a	nil	3.11 s	Inf/ 60.9^o

VI. THE SECOND DESIGN

In the second design, the velocity error is to be kept within 2% i.e. K_v = 1/0.02=50. From eqn. 3:

$$K_v = \lim_{s \to 0} \frac{10K(K_p + sK_d)}{s(s^2 + 4s + 8)} = 1.25K = 50 \qquad (3)$$

we get the value of the forward path gain: $K = 40$. This is a high value of gain, which makes the system unstable. Therefore, we add a lead compensator in the forward path to realize the specified stability margins and the time-domain characteristics. Simultaneously, we change the poles and zeroes of the compensator and reduce the rate feedback so as to keep the t-domain parameters within specified limits. Following an iterative procedure, the rate feedback has been fixed at: $K_d =$ 0.195 and the transfer function of the lead compensator has been taken as:

$$G_c(s) = \frac{1+0.1s}{1+0.005s} \tag{4}$$

Hence, the loop transfer function of the composite system is given as:

$$GH(s) = \frac{10K(1+0.2s)}{s(s^2+8s+4)} x \frac{1+0.1s}{1+0.005s}$$

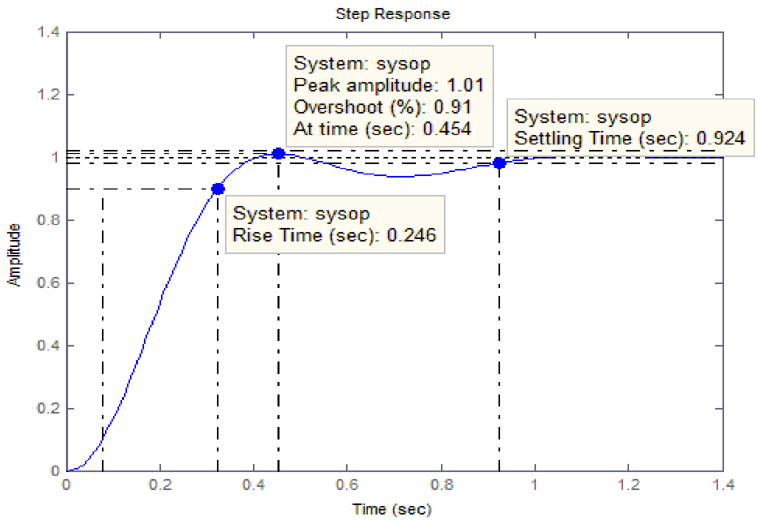

Fig. 11. t-domain response of the compensated system against step input

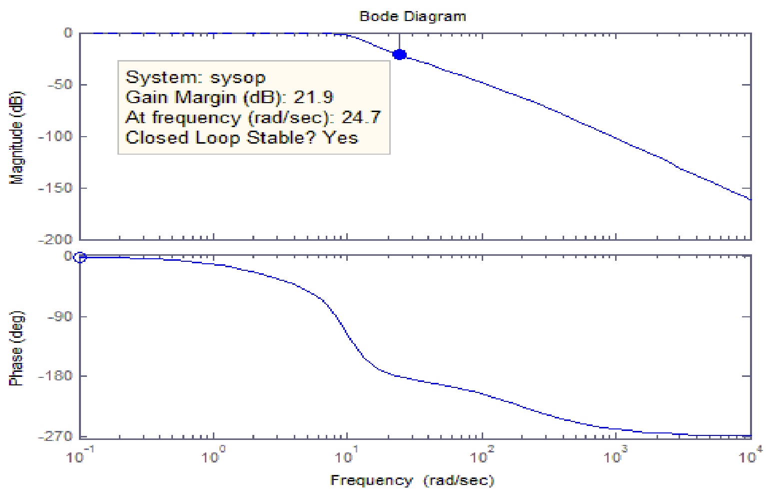

Fig. 12. Bode plot of the compensated system

The t-domain response against a step input and the Bode plot of the system with lead compensator are given in fig. 11 and fig. 12. It is found that the system is slightly under damped. The peak response has an overshoot of 0.91% and the peak time is 0.454 s . The rise time and the settling times are 0.313 s and 0.924 s respectively. The gain margin is 21.9 db which occurs at 21.4 r/s and the phase margin is 180^{o}. Further verification of the results obtained has been made by Nyquist plot and Nichols chart, given in fig. 13 & 14, respectively.

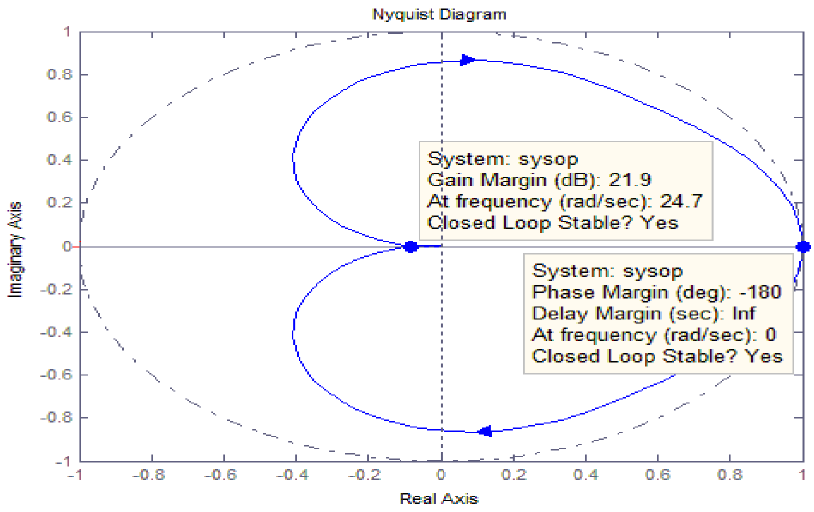

Fig., 13. Nyquist plot of the compensated system.

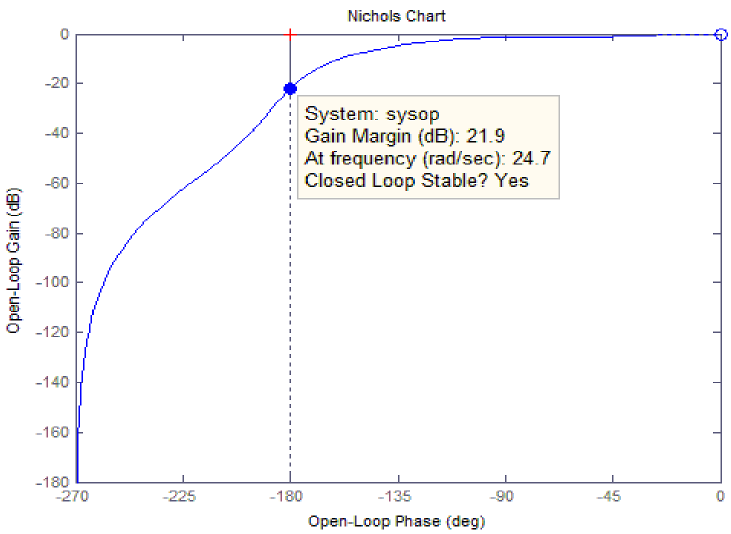

Fig., 14. Nichol's chart of the compensated system

Therefore, the insertion of a properly designed lead compensator has fulfilled all the specifications.

VII. CONCLUSION

Once upon a time we could only dream about the space but now we have achieved it at least partially. We are embarking upon the space age. Already we have undertaken many space exploration programs with great success. Advances in control system have made it possible to travel through space quickly and safely. Commercial models are expected to come up very soon [16].

There are also military applications of space vehicles. They were first developed by Germany during WW1 (Viking 1 & 2). Much progress in missile technology has been made since then.

The control of space vehicles is a vital part of all our space programs. In this paper, the way to design proper control systems for roll attitude control of a guided missile against given specs has been shown. The pitch attitude and yaw can be controlled by similar methods. The block diagram and transfer function of the systems have been collected from published literature [7].

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